INVESTIGATION OF A RELATIVISTIC KLYSTRON SCHEME.

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Abstract:

A scheme to generate microwave power with a high conversion efficiency has been investigated theoretically. In the scheme microwave power at 10 GHz is generated by conversion of electron energy of a relativistic electron beam. Periodic deflection of the electron beam is used to yield time of flight bunching due to modulation of the length of the trajectory rather than modulation of the speed of the electrons. Numerical simulation predicted a conversion efficiency for a finite emittance beam at an electron energy of 1 MeV of about 55%. For budgetary reasons the design value for an experimental investigation was reduced to 100 keV electron energy. The predicted conversion efficiency did not change significantly. An experimental set up was built. Measurements on parts of the system were performed. A quality factor of about 6400 was measured in a single cell cavity resonator compared to the theoretical value of about 8800 . A beam current of about 100 mA was indicated at an extraction voltage of 3.5 keV in a preliminary measurement. The theoretical and experimental investigation is continued as part of the MURI activities.

I. INTRODUCTION:

Efficient microwave generation relies on a modulated electron beam interacting with RF fields in a resonator or wave guide. The modulation of the electron beam is achieved in a conventional klystron by periodic energy modulation in a buncher cavity followed by a drift space. For relativistic particle beams the energy modulation results in a very small speed modulation and is not practical.

To modulate the electron current, a periodic deflection of the electron beam is used together with a 270° deflection in a magnetic field. Electrons travel different distances to the end of the magnet and periodically form bunches. Figure 1 shows the scheme.

The expected advantages are multiple. To achieve the same microwave power, the beam current can be reduced proportional to $1/(\gamma-1)$, where γ is the relativistic factor. There is an additional reduction of the beam spreading due to the reduced poissance of the electron beam, which reduces the self-fields by a factor $1/\gamma^2$. The spread of the free electron beam decreases therefore by an additional factor $1/\gamma^{1.5}$. This means that the beam spread diminishes for larger values of γ as $1/\gamma^{2.5}$. For a steady beam containment the magnetic focusing field scales with $1/\gamma^3$ for the same beam power. The requirements on the cathode and the beam transport system get relaxed as γ increases. Further the longitudinal dynamics are less affected by the space charge since the particles have a speed close to the speed of light for most of the trajectory in the interaction cavity. This allows the electron bunches to pass the interaction cavity at a phase angle for maximum deceleration.

Instead, the electrons have to be accelerated to higher energies, which requires a high voltage source. High voltage generators, especially pulsed modulators, are well developed. The shielding considerations are different for a relativistic electron beam. The Bremsstrahlung radiation is harder and emitted in forward direction.

Lowest order calculations show, that for an electron beam with energy 1 MeV a theoretical conversion efficiency of 65% could be achieved. Due to budget restraints the experimental investigation will be performed with 100 keV electron energy at a frequency of 10 GHz. Extension to higher frequencies should be possible by modification of the geometry of the source and the decelerator and by increasing the field in the solenoids.

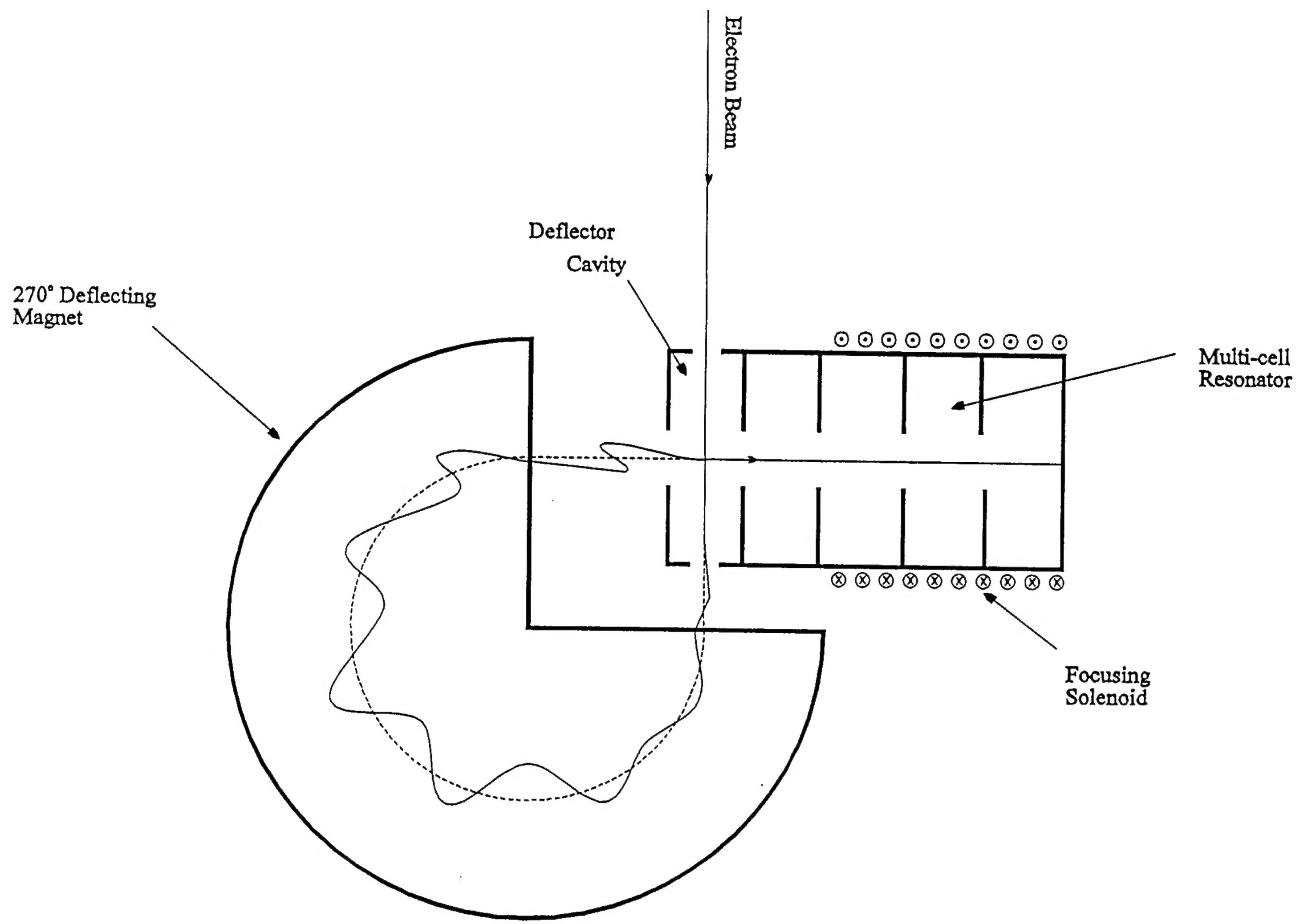

FIG. 1. Relativistic Klystron Scheme

II. THEORETICAL CONSIDERATIONS:

Interaction of a bunched electron beam of energy 1 MeV with a 13-cell decelerating cavity:

<u>MAGIC simulation:</u>

The interaction of a bunched electron beam was investigated with the MAGIC code. The TM_{010} cavity mode was excited in the π-coupling mode of the 13-cell structure. In order to get this mode excited the beam has to be modulated at the resonant frequency of the desired mode and the decelerating field has to have the correct magnitude. This balance can be achieved in the simulation by adjusting the beam current and the loading of the cavity. The loading of the cavity was achieved by making the space inside the cavity slightly conducting. In addition a focusing axial magnetic field of 0.20 T was applied to contain the beam transversely. The conversion efficiency achieved was 54%. Small changes in the operating parameters can cause a loss of the π-mode operation. In order to speed up the simulation, a beam current of 23.3 A and a quality factor of Q=70 were used. This is a larger current and a smaller quality factor than would practically be used in a klystron. The initial emittance of the beam was $\varepsilon = \pi r_0 r_0' = 6.54 \pi$ cm mrad .

The bunching parameter X was changed and the dependence of the efficiency on it is shown in figure 2. The optimum bunching factor was X = 1.2 .

The excitation of the structure, as a function of time, is shown in figure 3. The field is the axial electric field intensity near the axis of the 5th cell. The electric field in all cells was monitored to confirm the correct coupling mode and flatness of the field distribution. Figure 4 shows the electric field intensity at some suitable time in the 13-cell structure.

The various coupling modes were excited in a separate simulation by passage of two oppositely charged particles moving in opposite directions. Figure 5 shows the dispersion curve for the various coupling modes. The frequency spread between the 0-mode and the π–mode was about 5%.

The radius of the cavities was 12.13 mm and the total length of the structure was 166.4 mm. The aperture radius was 5.28 mm and the thickness of the aperture walls was 1 mm.

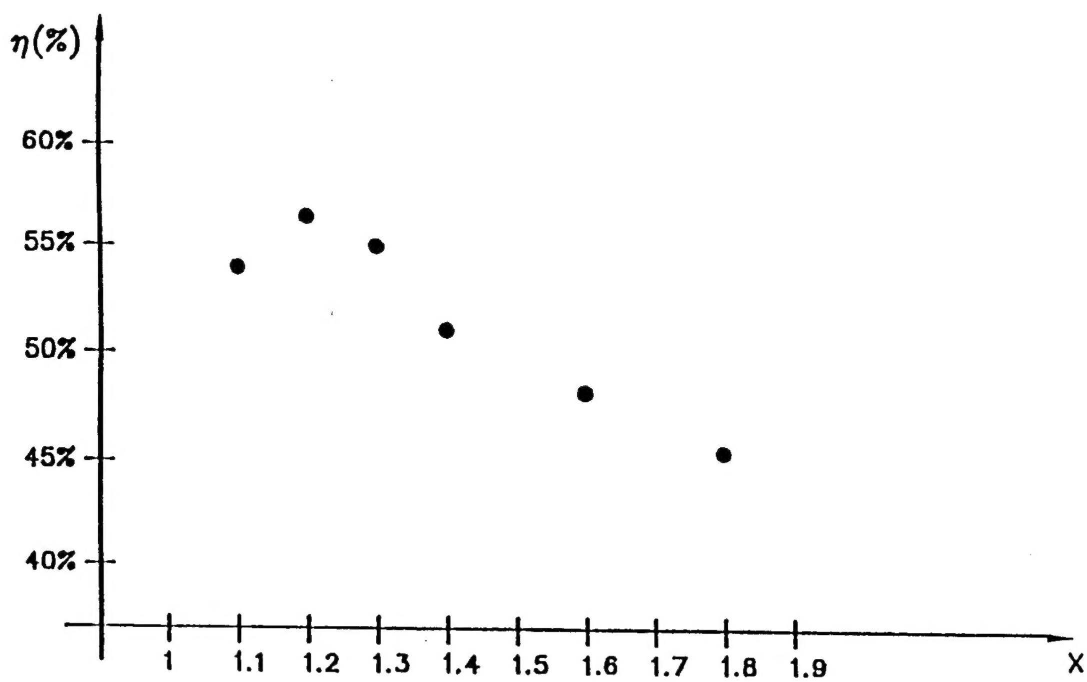

FIG. 2. Efficiency Versus Bunching Parameter X

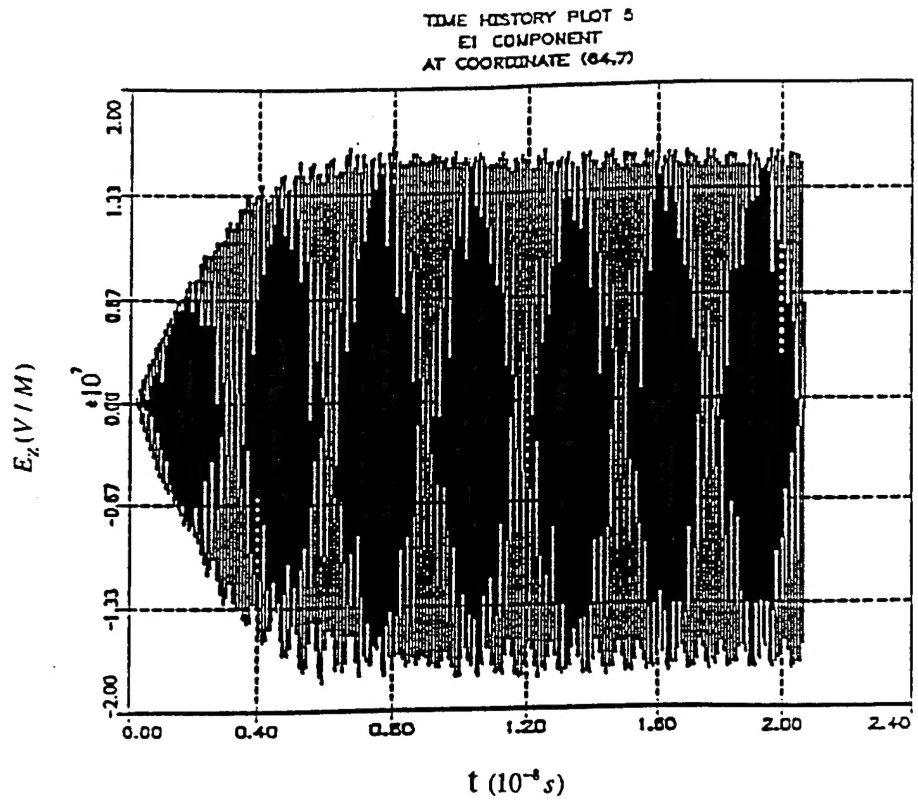

FIG. 3. Excitation of the RF-Field in the 5th Cell

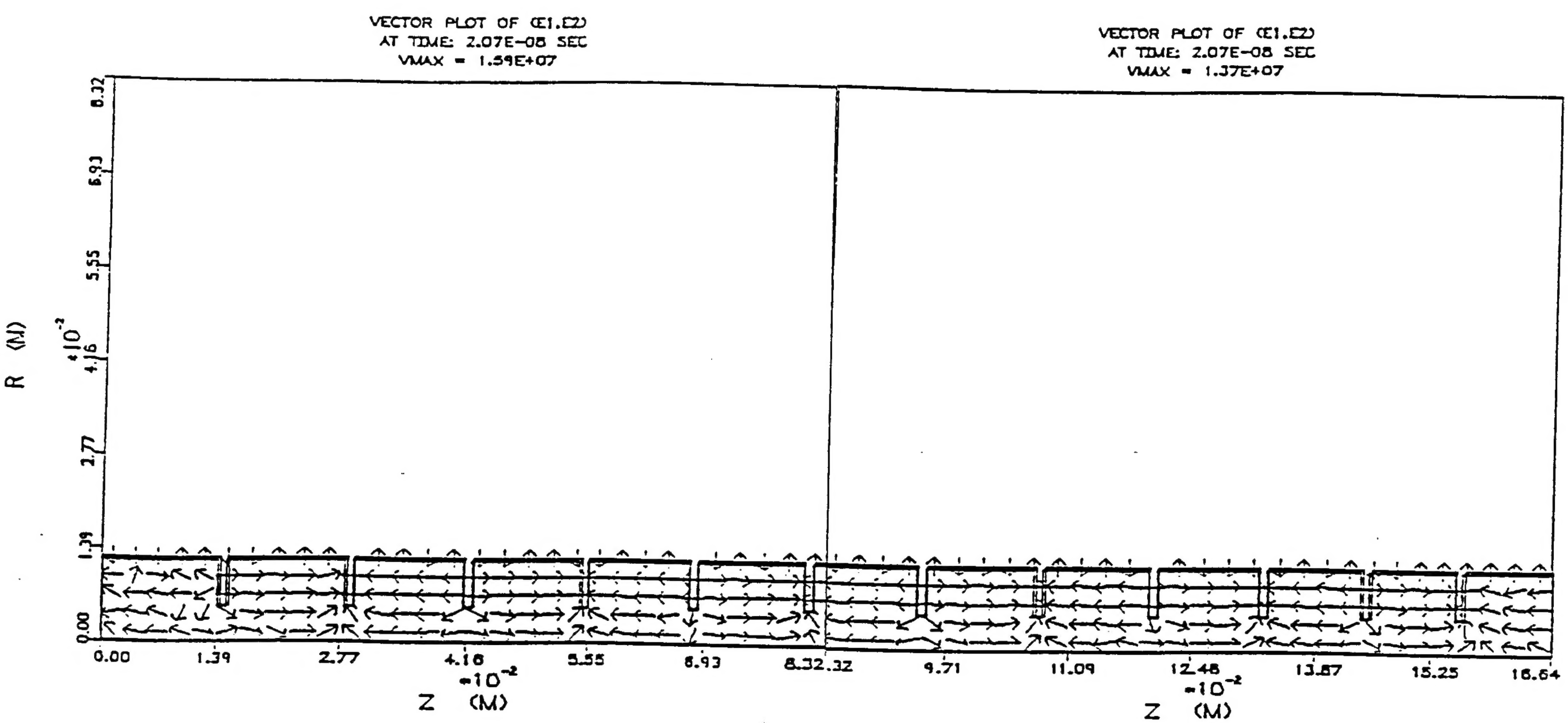

FIG. 4. Electric Field Intensity at t=20.7 nsec

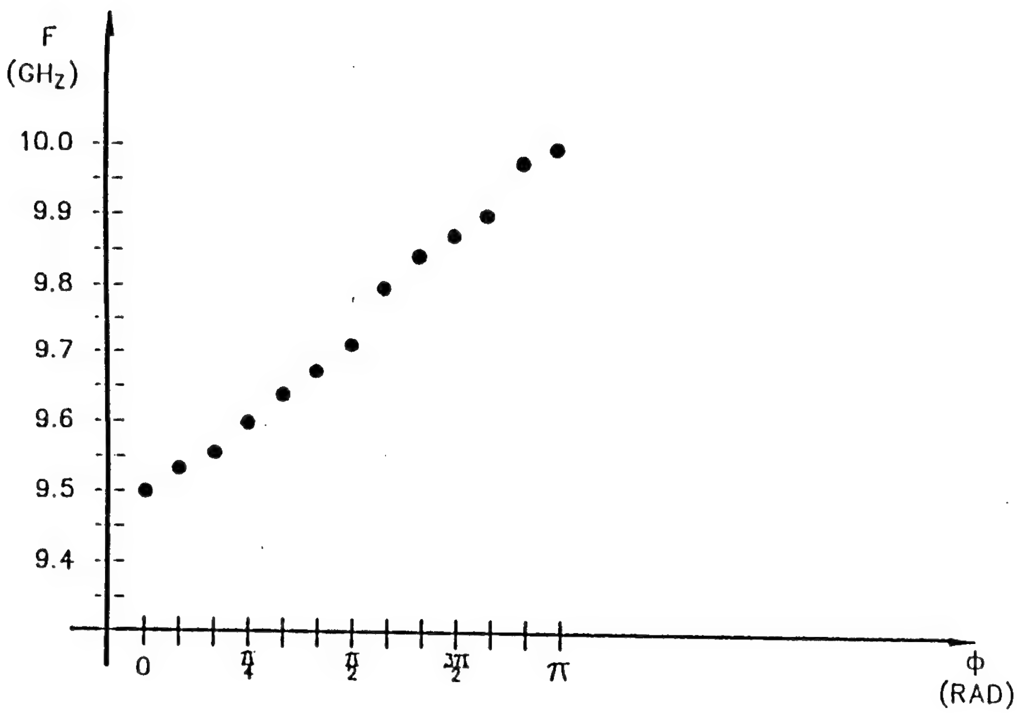

FIG. 5. Dispersion of the Coupling Modes

Simulation using a linear approximation of the particle trajectories:

In an attempt to simulate the klystron scheme in three dimensions, a linear approximation for the transverse dynamics of the electron beam was used. Self-fields were neglected in the simulation.

An electron beam enters a beam transport line through a deflecting cavity and a subsequent deflecting sector magnet. Subsequently it travels through a second multi-cell structure to a beam stop. The various components are separated by drift spaces which can be described by simple transfer matrices. An external magnetostatic field is applied in the decelerator region to prevent divergence of the beam in the decelerator region. Each beam optical element is described in the transverse plane by a transfer matrix. The transverse dynamics in the linear approximation can be described by simple matrix multiplications with a particle vector in 6-dimensional trace space.

The injected electron beam is represented by 25 particles and 40 phase values. All electrons have the same initial energy of 1 MeV. The initial two-dimensional emittance is $\varepsilon = 1.5\ \pi$ cm mrad. In transverse phase space 24 electrons are characterized by points on a 4-dimensional hyperellipse. There is one additional particle for each phase value at the center of the ellipse. One of the central particles is designated as the reference particle with reference position z_{ref}.

The transfer matrix for a drift space of length L is given by

$$\begin{bmatrix} x_f \\ x_f' \\ y_f \\ y_f' \\ \phi_f \\ (\beta\gamma)_f \end{bmatrix} = \begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} x_i \\ x_i' \\ y_i \\ y_i' \\ \phi_i \\ (\beta\gamma)_i \end{bmatrix} ,$$

where i and f indicate the particle coordinates entering and leaving the beam optical element respectively.

The deflecting cavity changes the slope of the trajectory relative to the beam axis: $x_f' = x_i' + \Delta x'_0 \sin(-\phi)$, where $\phi = -2\pi/\beta\lambda_0 * (z - z_{ref})$ and z_{ref} is the position of the reference particle on the beam axis.

The action of the sector magnet is given by the following transfer matrix

$$
\begin{bmatrix} x_f \\ x_f' \\ y_f \\ y_f' \\ \phi_f \\ (\beta\gamma)_f \end{bmatrix} = \begin{bmatrix} c_x & s_x & 0 & 0 & 0 & 0 \\ -s_x k_x^2 & c_x & 0 & 0 & 0 & 0 \\ 0 & 0 & c_y & s_y & 0 & 0 \\ 0 & 0 & -s_y k_y^2 & c_y & 0 & 0 \\ \dfrac{s_x 2\pi}{\rho_0 \beta\lambda} & \dfrac{1-c_x}{k_x^2 \rho_0} \dfrac{2\pi}{\beta\lambda} & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} x_i \\ x_i' \\ y_i \\ y_i' \\ \phi_i \\ (\beta\gamma)_i \end{bmatrix} ,
$$

where $$s_x = \frac{\rho_0}{\sqrt{1-n}} \sin(\sqrt{1-n}\psi) \qquad s_y = \frac{\rho_0}{\sqrt{n}} \sin(\sqrt{n}\psi)$$

$$c_x = \cos(\sqrt{1-n}\psi) \qquad c_y = \cos(\sqrt{n}\psi)$$

$$k_x = \frac{\sqrt{1-n}}{\rho_0} \qquad k_x = \frac{\sqrt{n}}{\rho_0} .$$

ψ is the angle of deflection of the sector magnet and $\rho_0 = \beta\gamma m_0/e_0 B_y(\rho_0)$ the radius of curvature of the beam axis in the deflecting magnet. The field index is defined as

$$n = -\frac{\rho_0}{B_y(\rho_0)} \frac{\partial B_y}{\partial x} .$$

The electric field intensity of the decelerating field is approximated by

$$E_z(z,t) = E_0 \sin\omega t \sin\int_0^z k(w)dw ,$$

where $k(\omega) = 2\pi/\beta\lambda_0$. The synchronous phase of the reference particle is

$$\phi_s = \omega t - \int_0^z k(w)dw .$$

The net effect of this can be derived as

$$\frac{d\beta}{dw} = -\frac{e}{m_0 c^2} \frac{E_0 \sin(\omega t(w) \sin(\omega\tau - \phi_s)}{\beta\gamma\left((\beta\gamma)^2 + 1\right)} ,$$

where $\tau = \tau_{old} + \Delta w/\beta c$, $\phi = (\tau - \tau_{ref})/w$, and τ_{ref} is the travel time of the reference particle in the resonator. The equation is integrated numerically.

A magnetic field is applied in the region of the decelerating structure. It is parallel to the axis except at the ends. The axial component of the fringe field on axis is approximated by a $\sin^2$ function and joined by a constant field in-between as shown in figure 6. This yields simple linear radial fields at the ends.

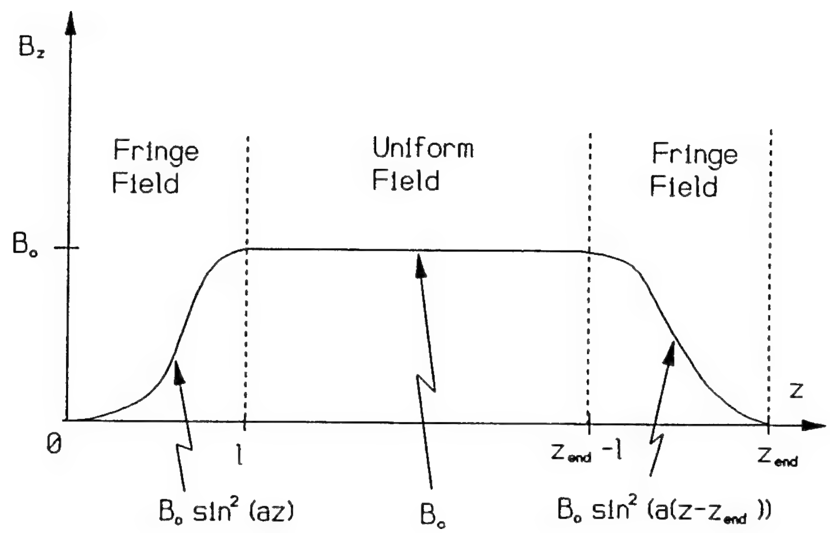

FIG. 6. Magnetic Field Intensity of the Solenoid on Axis

$$B_x = -x\frac{\pi B_0}{4l}\sin\left(\pi\frac{z}{l}\right) \qquad B_y = -y\frac{\pi B_0}{4l}\sin\left(\pi\frac{z}{l}\right) \qquad \text{for } 0<=z<=1.$$

The action of each element was tested for an analytically tractable case to verify the simulation.

The conversion efficiency η of beam power into microwave power is shown in figure 7 for various values of the synchronous phase ϕ_s and bunching parameter X. The emittance in this case was $\varepsilon = 0.71\ \pi$ cm mrad. Figure 8 shows the maximum efficiency versus the emittance for X=1.7 and ϕ_s=-35^0.

The maximum conversion efficiency $\eta = 54\%$ for a beam with an emittance of 0.71 π cm mrad was obtained for a bunching factor X=1.7 and a synchronous phase of ϕ_s=-30^0. The maximum beam radius inside the cavity is less than 2 mm for most of the electrons. Some electrons deviate from the axis up to 6 mm near the end of the resonator as shown in figure 9.

Simulations for a beam energy of 100 keV:

Since the realization of a 1 MeV experiment was outside the financial means, due to budget cuts, a smaller system was designed, which could operate with a beam energy of 100 keV. The source for this system was first a thermionic emitter. It was realized, that under the practical limitations a thermionic emitter would not last very long. Also the vacuum system would have to be improved significantly. It was therefore decided to use a insensitive plasma edge cathode scheme to produce a pulsed electron beam.

The system was simulated in two dimensions using the MAGIC code. The simulation includes the bunching of the beam and the feedback of the energy by the bunched beam. The klystron, using only one cavity, oscillates and reaches a state of saturation as dissipation and over-bunching limit the microwave energy in the system. The extension to more than one cell is in progress.

The linear three-dimensional code was also applied to the new energy of 100 keV. The results are depicted in figure 10 and figure 11. The maximum conversion efficiency is still of order 55%.

The beam generation and acceleration in the electron gun has been simulated using MAGIC and the design parameters have been determined. The design uses three electrodes. The electrode at 4 kV can be used to gate the beam. This would become necessary to limit the average beam power and dissipation in the system in case a thermionic emitter were used. The sensitivity of the beam geometry to changes of the various parameters of the gun has been also investigated and there appears to be no excessively tight tolerances involved. The source for this simulation was a thermionic

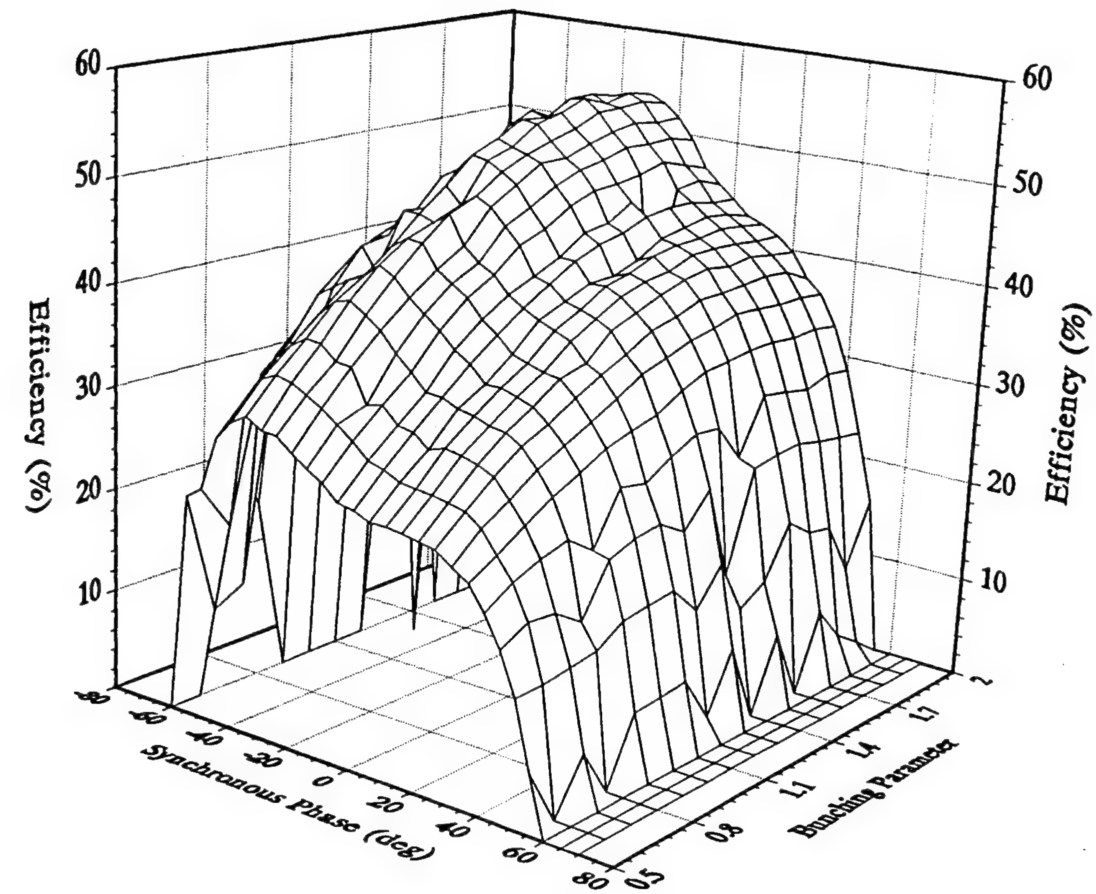

FIG. 7. Efficiency for 1 MeV Electrons and an Emittance of 0.71π cm mrad

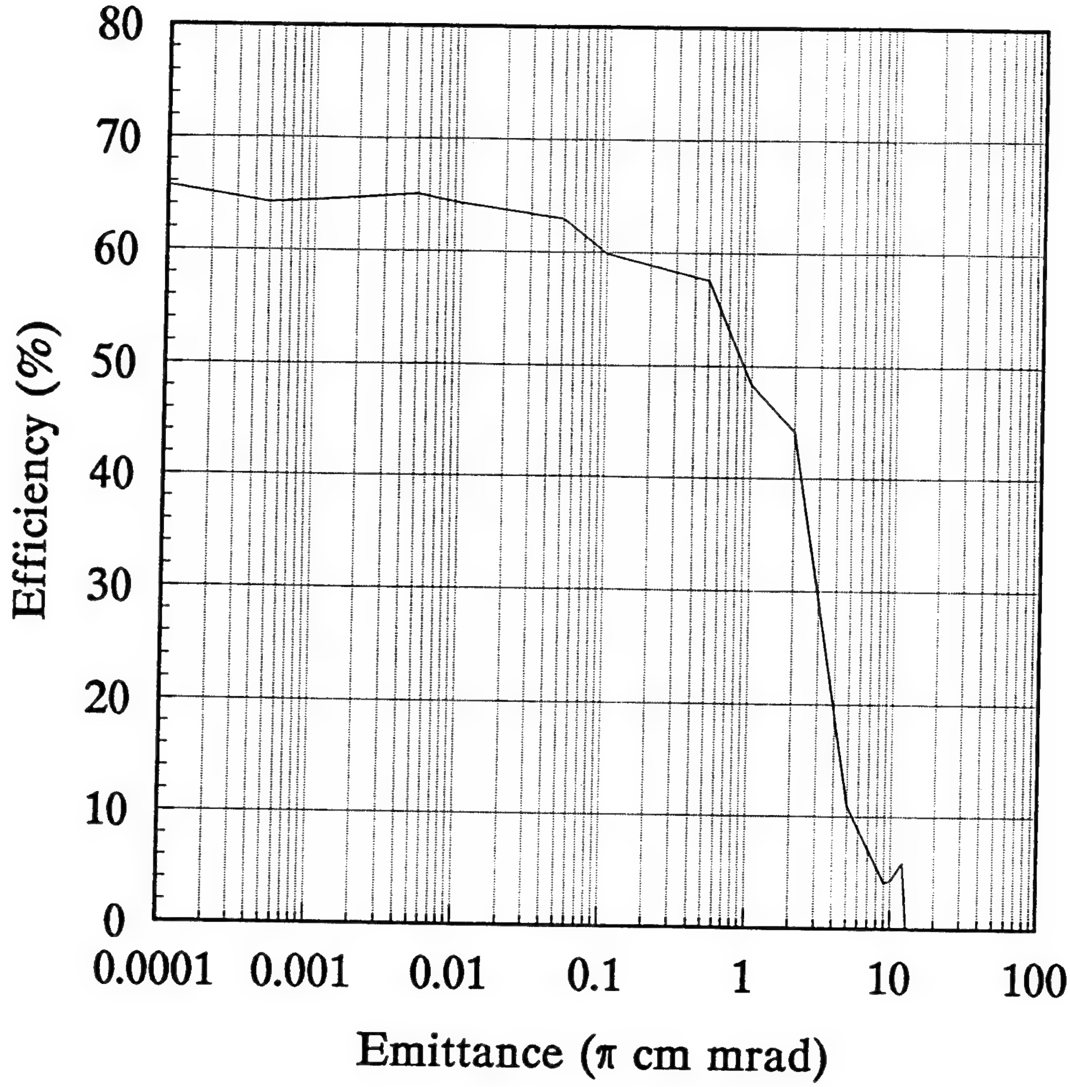

FIG. 8. Efficiency for 1 MeV Electrons ($X=1.7$ and $\phi_s=-35^0$)

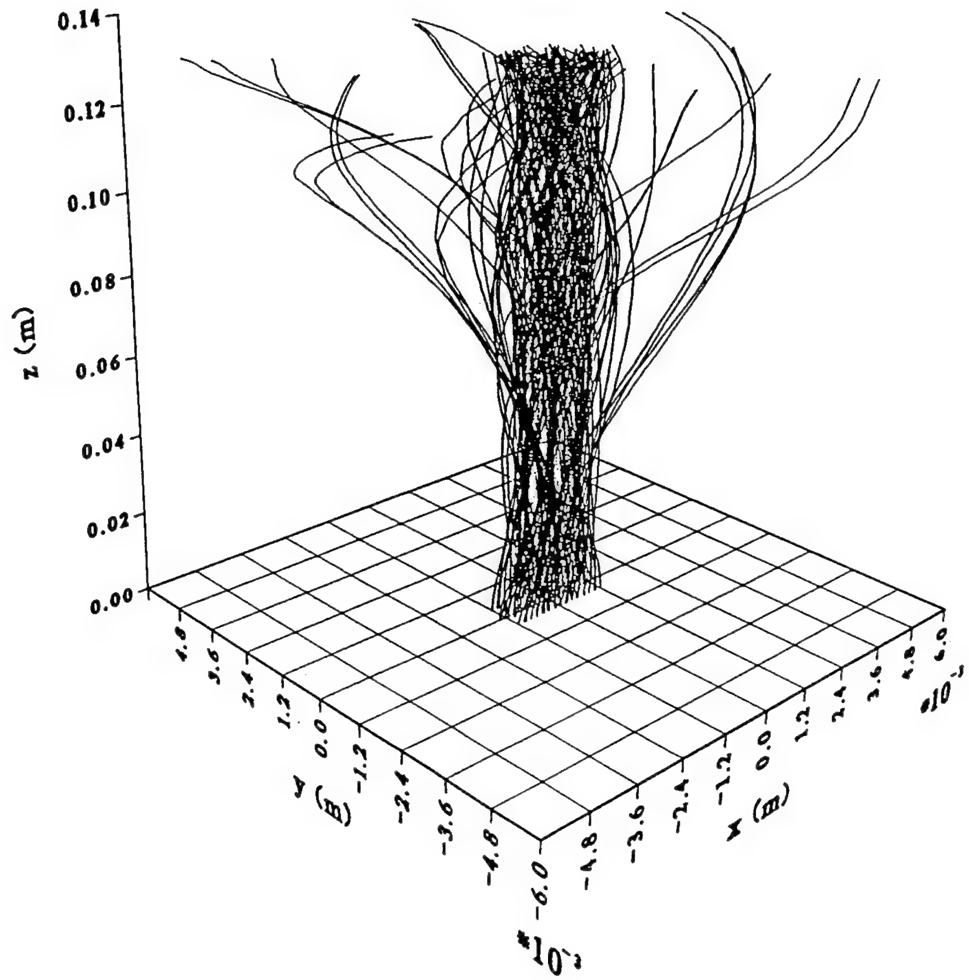

FIG. 9. Electron Traces at the Decelerating Cavity

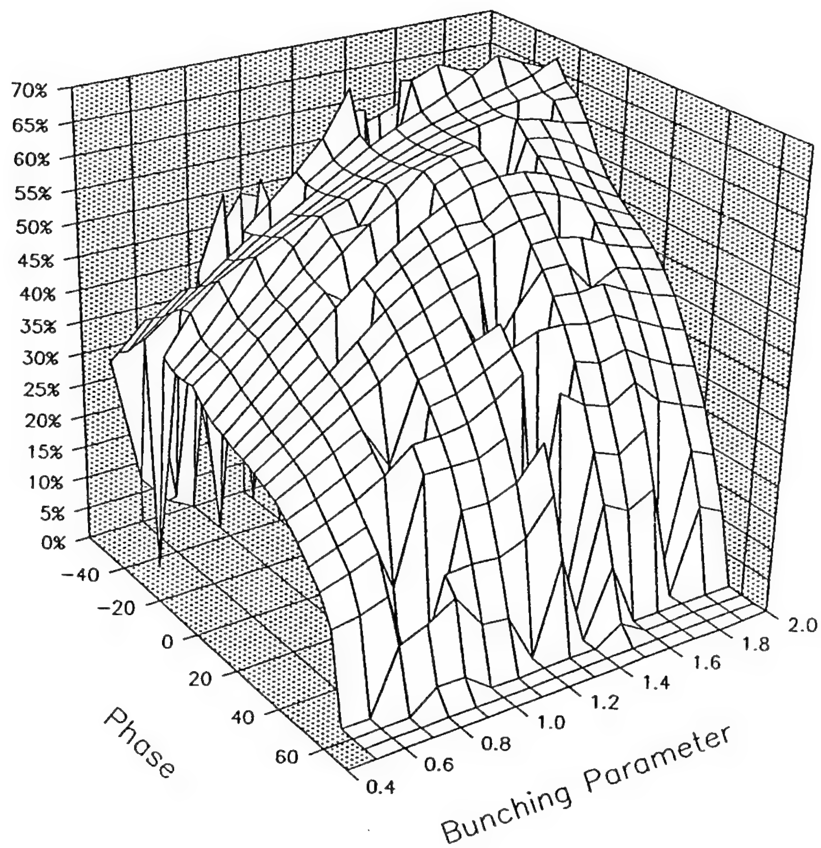

FIG. 10. Efficiency for 100 keV Electrons and Zero Emittance

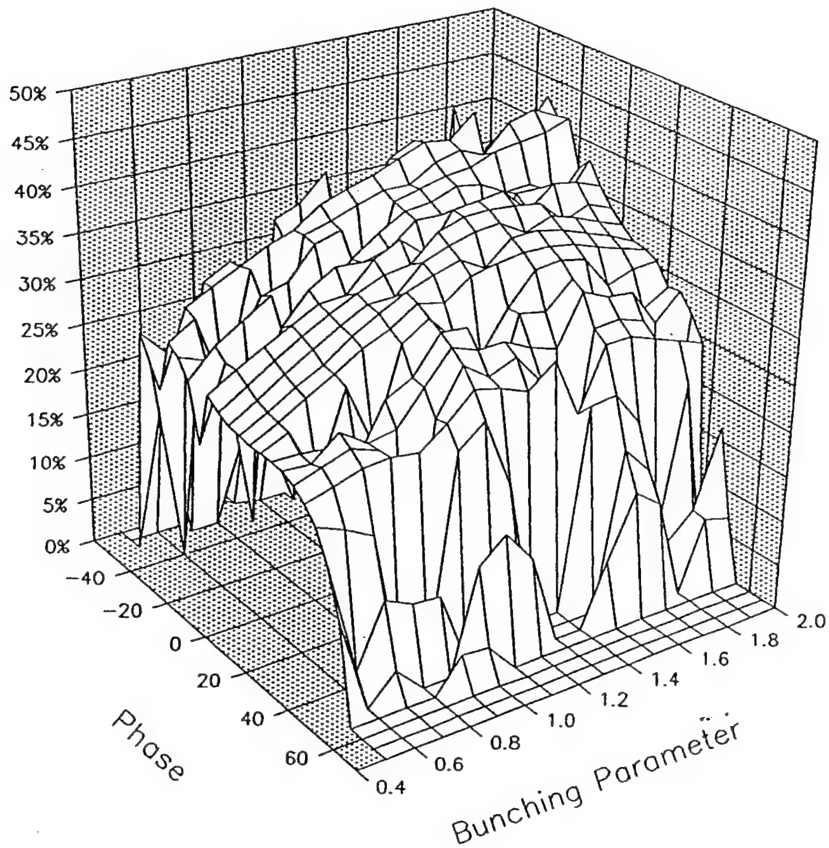

FIG. 11. Efficiency for 100 keV Electrons and an Emittance of 1.5π cm mrad

emitter, which has been replaced later by a plasma edge cathode scheme. Figure 12 shows the beam cross-section at the beam extraction region.

Figure 13 shows the result of a simulation of the hole system for one single cavity. The system oscillates at the appropriate frequency starting from a low seed value.

III. DESIGN AND EXPERIMENTAL SET UP:

The experimental arrangement consists of a vacuum enclosure which houses an electron source, an extraction channel, a post acceleration section, a 270^0 deflecting magnet, a five-cell cavity resonator, and finally a beam dump. The vacuum system uses conflat flanges and stainless steel and glass tubes. There are some parts, which limit the achievable vacuum to about 10-6 Torr. The pump is a oil diffusion pump connected to the vacuum system through a cold trap, which is cooled by freon from a refrigerator. Figure 14 shows an overview of the system.

Initially a thermionic emitter was used as an electron source, but was discarded due to the insufficient vacuum. Instead a plasma edge cathode scheme was installed. It is based on the space charge limited transverse extraction of an electron beam from a plasma jet. The plasma jet is generated by surface flashover on the insulator of a marine spark plug. The ions are predominantly aluminum and oxygen. The extraction potential is applied between the plasma scraper (Pierce electrode), which is on the same potential as the plasma gun, and the extraction electrode (Figure 15). The electron beam is accelerated further by an additional electrode which is at a potential of 100 kV relative to the plasma gun and the scraper (Figure 14). The accelerating electrodes are also serving for the electrostatic focusing of the electron beam. The extraction potential is presently 3.5 kV and no post-acceleration is used. The electron beam has been monitored by Faraday collectors. Detection by a fluorescent screen is planned for the near future.

The periodic deflection of the electron beam is achieved by the TM_{010} mode in the first cell of the five-cell cavity resonator. The beam traverses the cell transversely and is deflected by the azimuthal magnetic field (Figure 16). The transit time factor has a significant influence on the amplitude of the deflection. It has been tailored by hiding the beam from the electric field intensity inside the cavity.

After leaving the deflection cell the beam is deflected by the field of an inhomogeneous sector magnetic by an angle of 270^0 (Figure 16). The magnet is mounted inside the vacuum system. The deflecting magnet has been built but not installed yet in the system.

The bunched beam enters the cavity a second time parallel to the axis. The electron bunches are decelerated in the multi-cell cavity (Figure 17). The decelerating

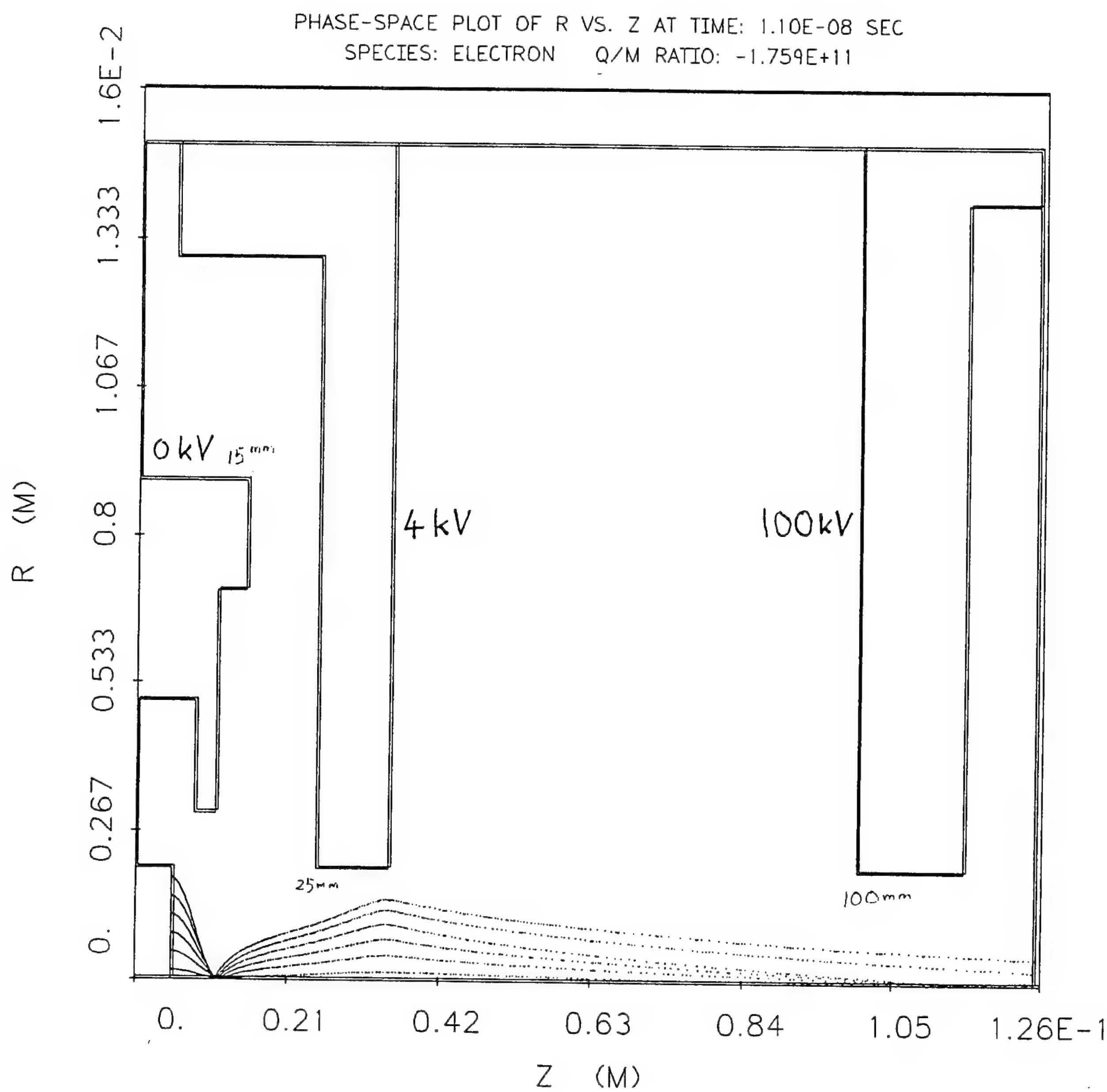

FIG. 12. Electron Extraction from a Thermionic Cathode and Acceleration

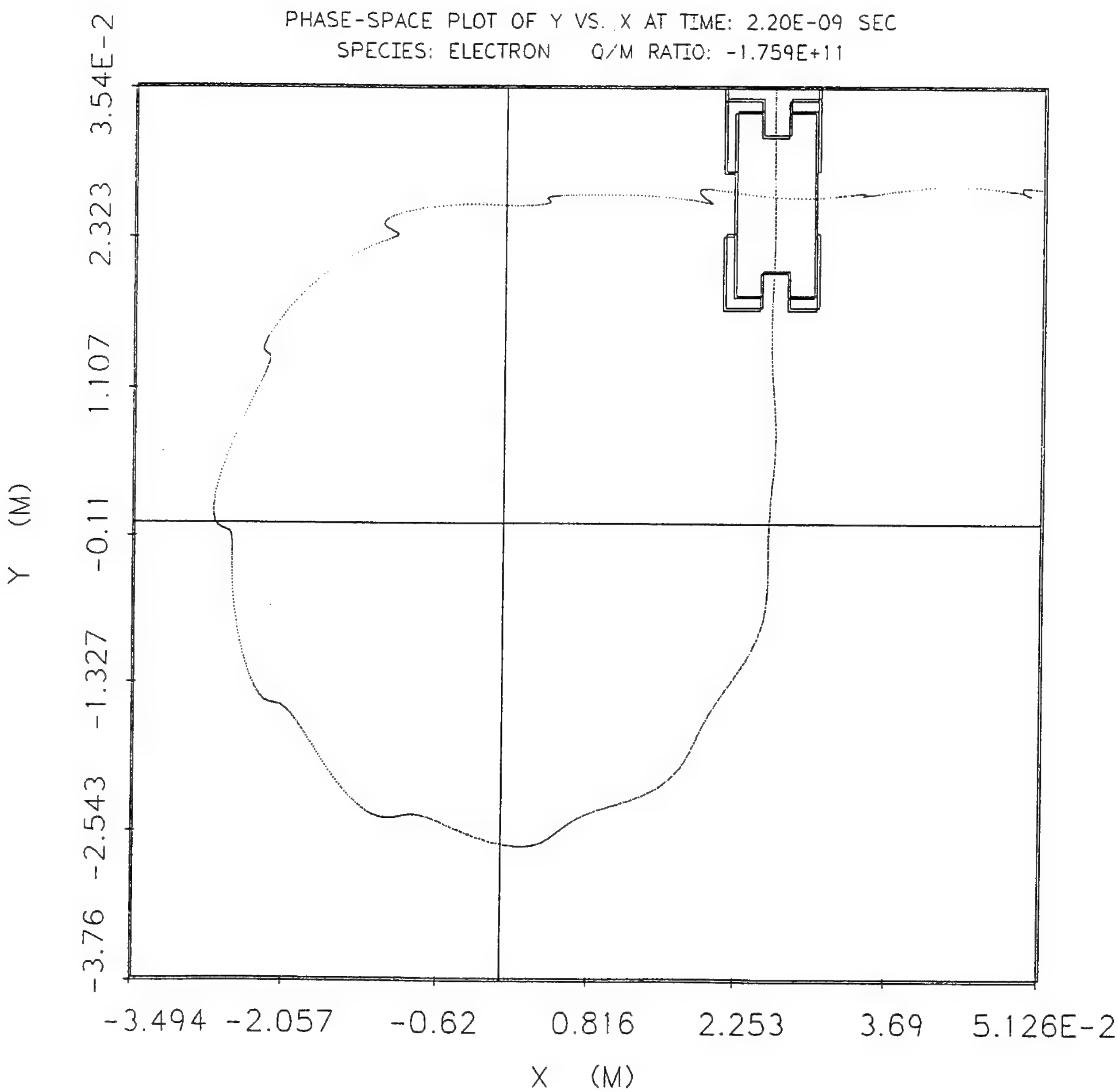

FIG. 13. MAGIC Simulation of a One-Cell Deflecting 10 GHz 100 keV Klystron

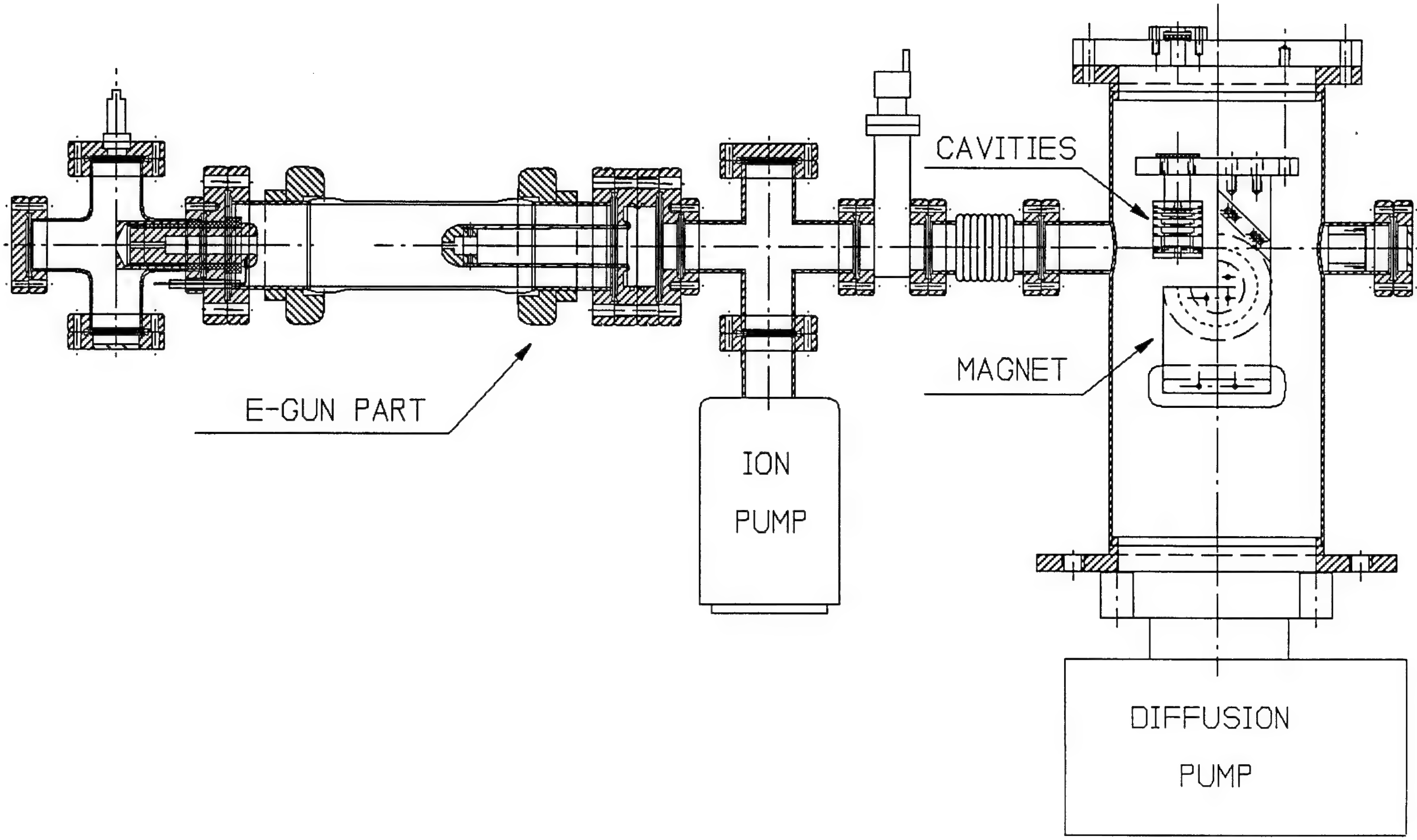

FIG. 14. Klystron Design

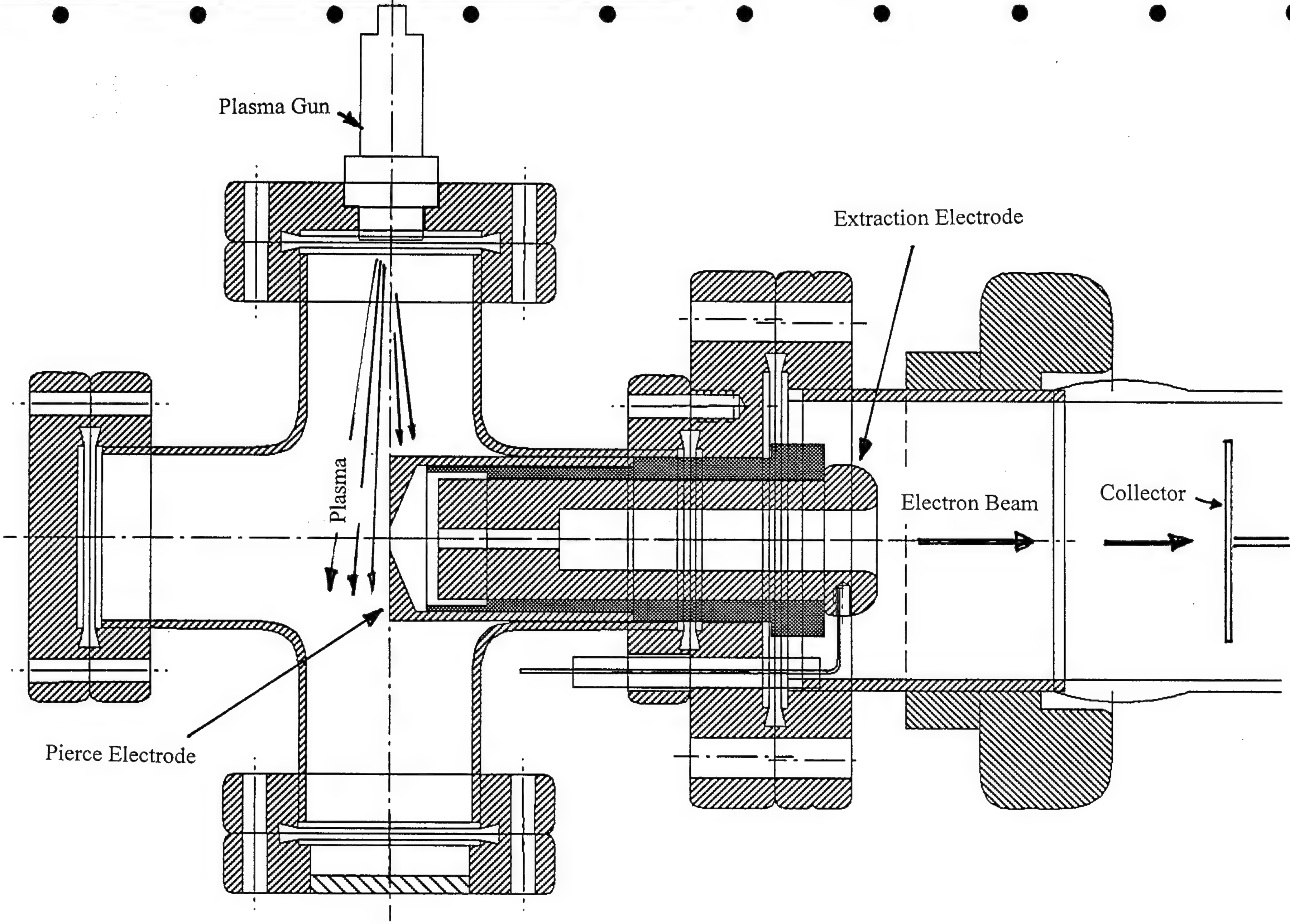

FIG. 15 Plasma Edge Cathode and Extraction

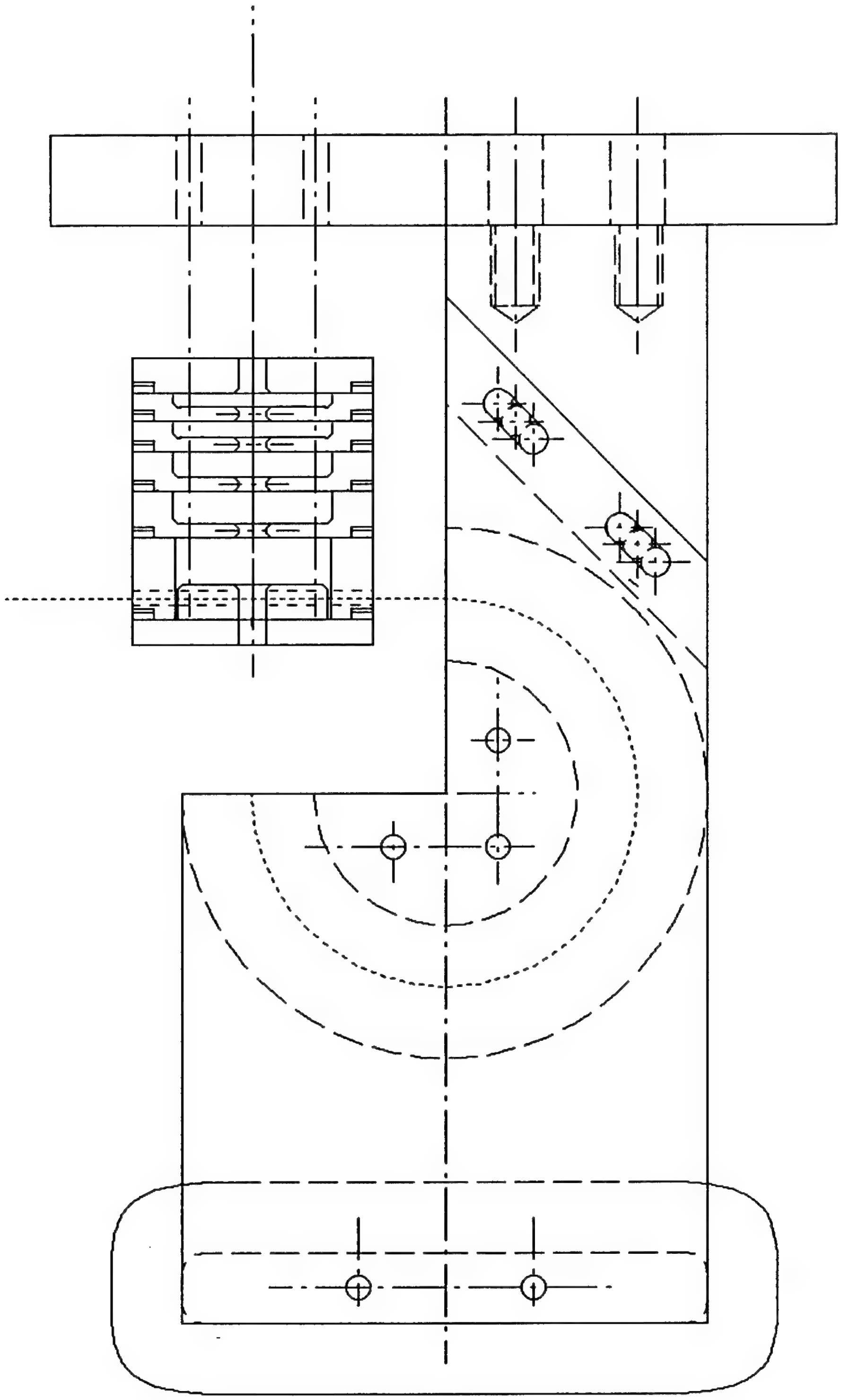

FIG. 16. Deflecting Magnet and 5-Cell Structure

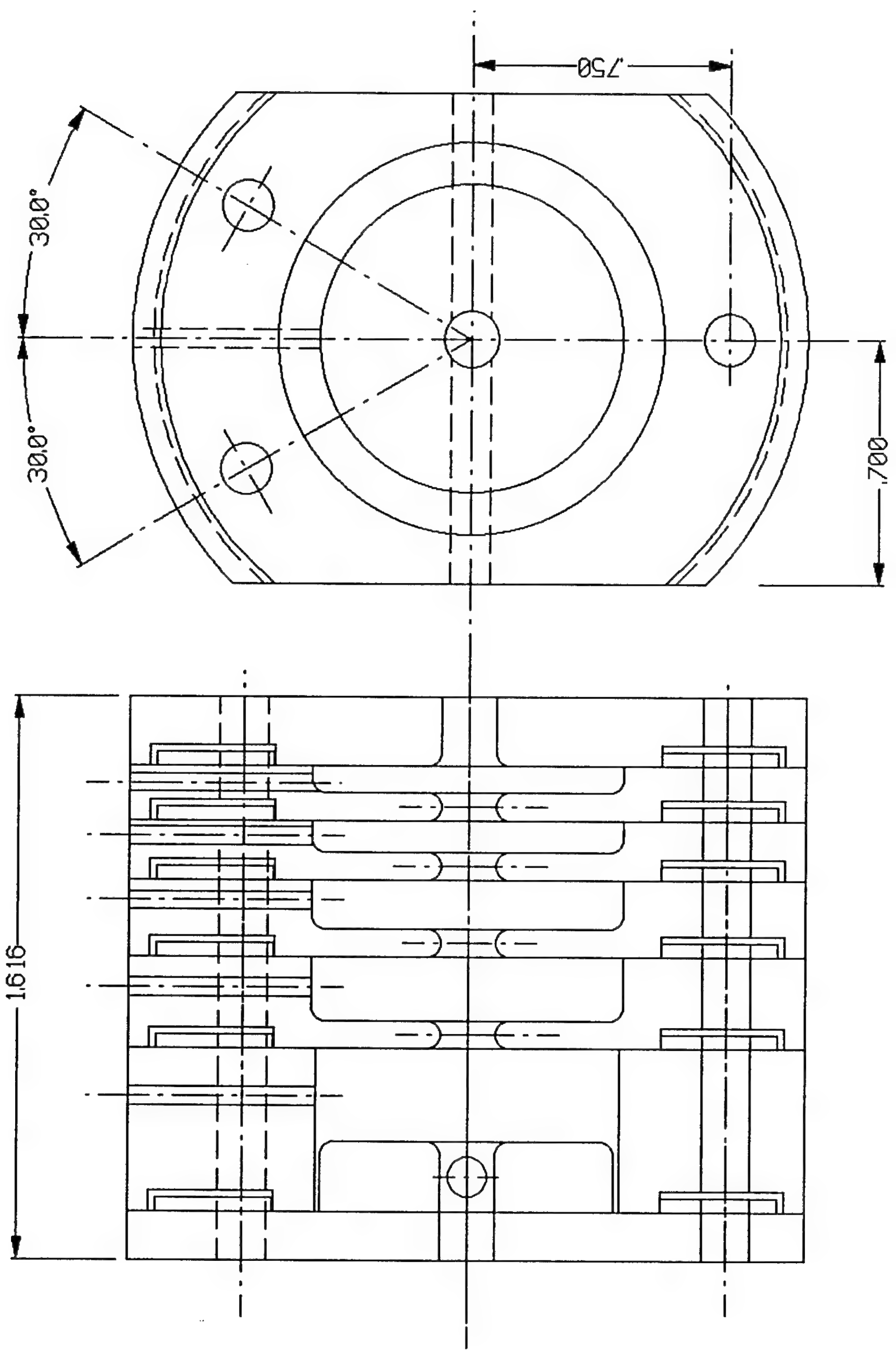

FIG. 17. Five-Cell Structure

cavity is made of copper cells, which are brazed together. The cells have holes on the outer cylinder to accommodate inductive coupling loops. The rigid coaxial transmission lines with the coupling loops have an outer diameter of 1.25 mm. The area of the coupling loop is about 1 mm^2. A cavity model made of aluminum has been built. The frequency of each cell has been determined. A 2% correction is indicated. This correction will be incorporated in the near future. It was found for a copper model cavity, that the parts of the cavity have to be brazed in order to get a sufficient quality factor. The joint has to be at the rim of the cavity for manufacturing reasons. The maximum current is then flowing across the joint. Simply pressing the joint together does not yield a quality factor beyond about 500 and the quality factor is not reproducible for such a joint. A joint parallel to the resonator axis is more difficult to machine.

IV. MEASUREMENTS:

The resonance frequency and the quality factor for single-cell cavities has been measured. Figure 18 shows the response of a single cell clamped brass cavity with a loaded quality factor of about 300. The resonance frequency was within 0.5% of the design value. The unloaded quality factor for a single-cell brazed copper cavity was found to be about $Q_0 = 6400$. The theoretical value is close to 8800 .

Some measurements on the multi-cell structure have been performed, which indicated that the actual frequencies of the individual cells are 2% higher than the design frequency. These measurements are continued and corrections will be made.

The electron beam current from the electron gun was measured. Preliminary measurements indicate an electron current of about 100 mA at an extraction potential of 3.5 kV between the extraction electrode and the scraper. The pulse length appears to be about 25 μsec (Figure 19). These measurements are preliminary and have to be improved and extended.

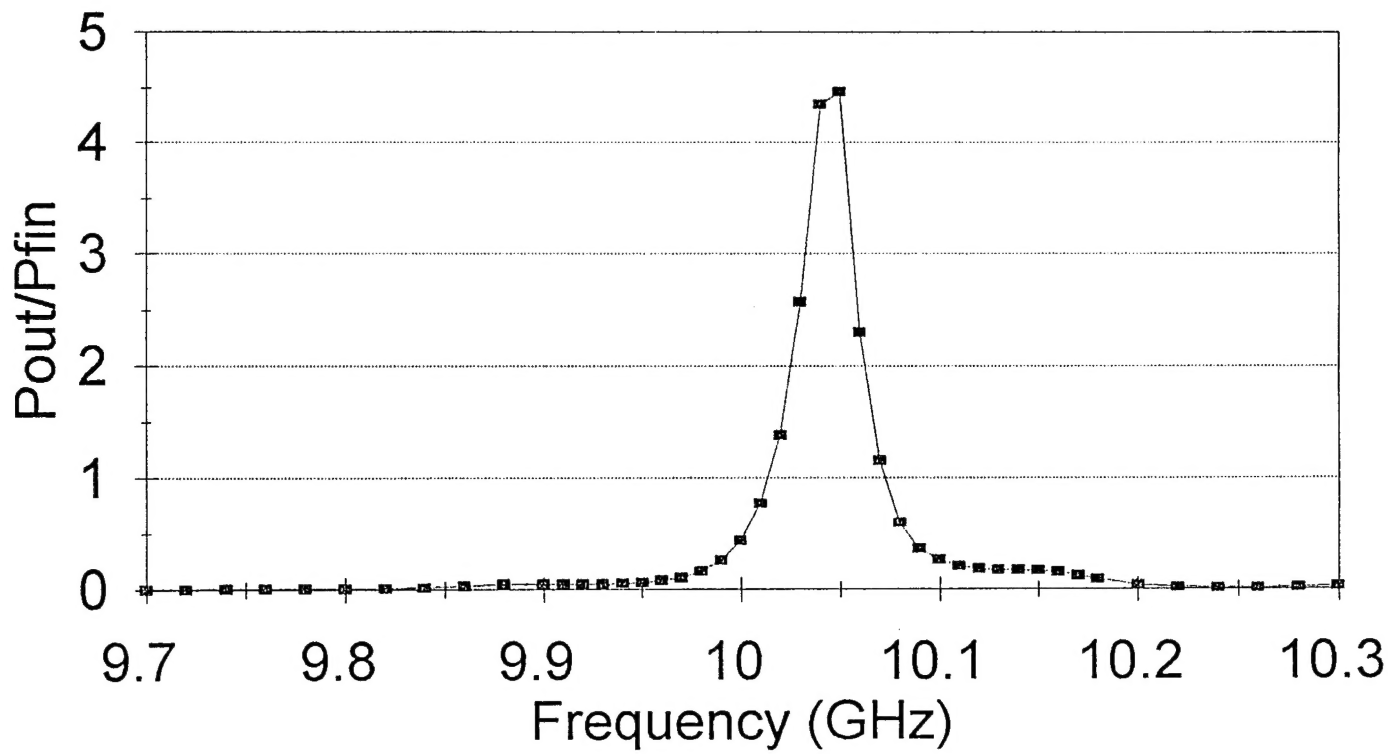

FIG. 18. Frequency Response of a Single-Cell Clamped Cavity

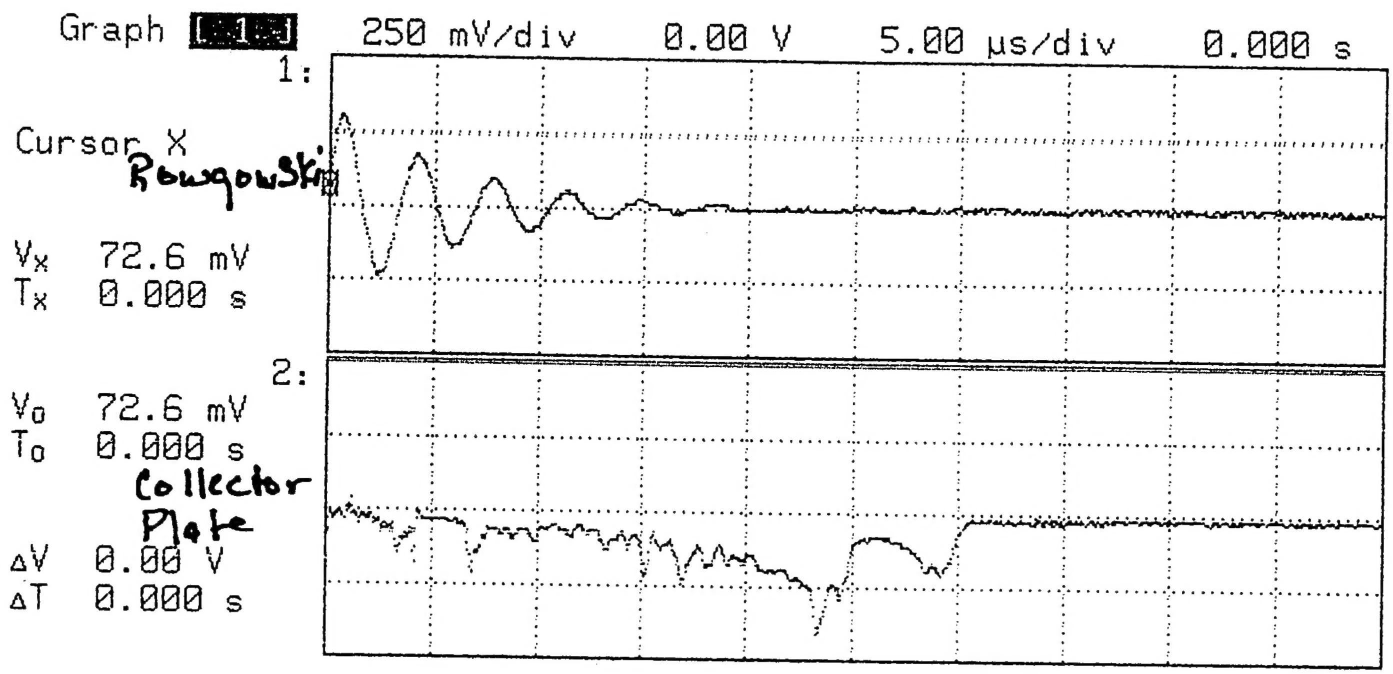

FIG. 19. Plasma Gun Current and Collected Beam Current

V. RESULTS:

The numerical simulation of the relativistic klystron shows that for a finite emittance beam a conversion efficiency around 50% can be expected. In the simulation the oscillation grew from a small seed value to saturation. The π-mode could be excited in the simulation when a bunched electron beam was injected into the multi-cell structure. Measurements on model cavities show that the final cavity has to be braced in order to have reproducible performance and low losses in the cavity. The electron source has to be further diagnosed. The investigation is continued both theoretically and experimentally.

VI. PARTICIPATING PROFESSIONAL PERSONNEL AND STUDENTS:

Klaus W. Zieher (Associate Professor) was participating in the research and supervising the students working on the relativistic klystron investigation.

David L. Roye (Graduate Student)

James G. Moring (Graduate Student)

Vince Tyson (Graduate Student)

Yongnan Liu (Graduate Student)

John Rybicki (Graduate Student)

Christopher K. Axton (Graduate Student)

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